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A NEW COLLAPSING TECHNIQUE FOR STAR IDENTIFICATION USING SENSORS WITH NONSIMULTANEOUS ACQUISITION TIMES

by
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A new stellar image mapping technique based on a state transition matrix form of solution for the rotational motion of a satellite is described. This technique allows star hits observed by an on-board sensor over a period of time to be effectively collapsed to an instantaneous photograph. When good rate gyro samples of the angular velocity are available, this collapsing is rigorous.

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FOREWORD

Precise satellite attitude estimation is becoming increasingly important for a large number of space vehicles. On-board stellar sensors can provide highly accurate orientation information once the imaged stars are identified. This report describes the development of a technique to aid in star identification for certain types of systems.

This work was performed in the Space and Surface Systems Division of the Strategic Systems Department at the Naval Surface Weapons Center, Dahlgren, Virginia.

The author expresses his appreciation to Dr. John L. Junkins, Virginia Polytechnic Institute and State University, for his constructive comments on this work, specifically with regards to the deterministic attitude computation after tentative identification of two stars.

This report has been reviewed and approved by Mr. Robert W. Hill, Head, Space Flight Sciences Branch, and Mr. Richard J. Anderle,Research Associate, Strategic Systems Department.

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DEFINITIONS OF SYMBOLS

$\{\hat{g}\}$	A unit vector triad defining the vehicle reference frame
$\{\hat{n}\}$	A unit vector triad defining inertial space
$[GN(t)]$	The direction cosine matrix that orients the vehicle axes relative to inertial space
$\omega_i(t)$ $(i = 1, 2, 3)$	Vehicle axes components of angular velocity
$\omega_{m_i}(t)$ $(i = 1, 2, 3)$	Rate gyro measurements of $\omega_i(t)$
$B_i (i = 1, 2, 3)$	Rate gyro biases
$[\Phi(t,t_0)]$	State transition matrix solution for vehicle motion
$\ell_{s_i}(t)$ $(i = 1, 2, 3)$	Instantaneous sensor-fixed direction cosines of the line of sight to a star
ℓ_{n_i} $(i = 1, 2, 3)$	Inertial coordinates of a star
$[SG]$	The direction cosine matrix that orients sensor axes relative to the vehicle reference frame
$\{\hat{u}\}$	A unit vector triad constructed from the lines of sight to two stars
$\hat{\ell}_j$	The unit vector to star j
$[A]$	The direction cosine matrix that orients $\{\hat{u}\}$ relative to the sensor axes
$[B]$	The direction cosine matrix that orients $\{\hat{u}\}$ relative to inertial space
$\{\hat{s}\}$	A unit vector triad defining the sensor reference frame

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INTRODUCTION

Many precise satellite attitude estimation systems utilize some type of on-board star sensing device. These devices provide very accurate measurements of stellar images which can be used with the inertial coordinates of the observed star to obtain vehicle orientation information. A key step in this is the identification of the imaged stars.

The star sensor of interest here can be thought of as an optical device which consists of a number of light-sensitive slits on an otherwise opaque negative image plane. As the vehicle rotates, images of stars cross the slits and the precise image plane coordinates and time of each transit are recorded. Due to the nature of these sensors, there will generally be no simultaneous hits by multiple stars. This nonsimultaneity of acquisition compounds the star identification problem. Traditionally, in this type of situation, a motion model for the vehicle is integrated to map all of the star hits into an estimated celestial coordinate frame. Then, star identification is attempted by either a direct match (overlay of imaged stars and catalog stars) or by comparisons of angular separations among catalog stars and imaged stars. There are two major difficulties with this mapping technique. First, errors in initial orientation can cause the estimated celestial frame to be substantially displaced from the true catalog frame. Second, errors in the rotational motion model effectively cause distortion in the mapped star field. Either of these problems can cause failure of a direct match algorithm. Angular separation algorithms are sensitive to distortions but are affected by initial errors only in that larger subsets of the reference catalog must be used for comparisons. This situation can quickly give rise to a prohibitive number of computations. Separately or in combination, these errors can easily lead to nonidentification of the star pattern. The only recourse in traditional methods is often brute force. Parameters of the motion model and/or the initial orientation are systematically stepped through a range of permissible values and identification is repeatedly attempted using one of the above techniques.

The new mapping technique described here provides an alternative approach where star hits are collapsed to an instantaneous sensor-fixed frame. Inherently contained in this technique is information that can be used to improve parameters of the motion model and thus decrease distortion effects. A two-stage star identification process then allows deterministic computation of the absolute vehicle attitude at the collapse time. This in turn, decreases computational problems due to errors in initial conditions.

DEVELOPMENT OF EQUATIONS

The differential equation for the direction cosine matrix that orients the vehicle fixed reference frame $\{\hat{g}\}$ relative to inertial space $\{\hat{n}\}$ is given by Reference 1.

$$[\dot{GN}(t)] = [\widetilde{\omega(t)}]^T [GN(t)] \tag{1}$$

where $$[\omega(\tilde{t})]^T = \begin{bmatrix} 0 & \omega_3(t) & -\omega_2(t) \\ -\omega_3(t) & 0 & \omega_1(t) \\ \omega_2(t) & -\omega_1(t) & 0 \end{bmatrix}$$

$\omega_i(t)$, ($i = 1, 2, 3$) are the $\{\hat{g}\}$ components of the inertial angular velocity. This equation is purely kinematic. Dynamics enter only through the determination of the angular velocity history. It is assumed in this development that good, dense, but discrete samples of $\omega_i(t)$ are available from an on-board rate gyro system. Under this assumption the entire problem becomes kinematic in nature with the motion characterized by Equation (1), which contains no explicit model errors. In this case,

$$\omega_i(t) = \omega_{m_i}(t) - B_i, \ (i = 1, 2, 3)$$

where $\omega_{m_i}(t)$ are the measured $\{\hat{g}\}$ components of the angular velocity and B_i are the components of the rate gyro bias vector.

It can be shown that (1) has a state transition matrix form of solution given by Reference 2.

$$[GN(t)] = [\Phi(t, t_0)] \ [GN(t_0)] \tag{2}$$

where $$[\dot{\Phi}(t, t_0)] = [\omega(\tilde{t})]^T \ [\Phi(t, t_0)] \tag{3}$$

with $$[\Phi(t_0, t_0)] = [I] \tag{4}$$

At a given star hit acquisition time, t, the inertial and sensor-fixed direction cosines of the line of sight to the star are related by

$$\begin{Bmatrix} \ell_{s_1}(t) \\ \ell_{s_2}(t) \\ \ell_{s_3}(t) \end{Bmatrix} = [SG] \ [GN(t)] \begin{Bmatrix} \ell_{n_1} \\ \ell_{n_2} \\ \ell_{n_3} \end{Bmatrix} \tag{5}$$

where $\ell_{s_i}(t)$, ($i = 1, 2, 3$) are measured or "sensor-observed" direction cosines to the star,

ℓ_{n_i}, ($i = 1, 2, 3$) are the unknown but time-independent inertial components of the line of sight to the star (the "celestial coordinates"), and [SG] is the constant rotation matrix which orients the sensor-fixed reference frame, $\{\hat{s}\}$, relative to $\{\hat{g}\}$.

The effective sensor-fixed direction cosines at some arbitrary epoch (say t_0) of the star that was actually acquired at t are

$$\begin{Bmatrix} \ell_{s_1}(t_0) \\ \ell_{s_2}(t_0) \\ \ell_{s_3}(t_0) \end{Bmatrix} = [SG]\ [GN(t_0)] \begin{Bmatrix} \ell_{n_1} \\ \ell_{n_2} \\ \ell_{n_3} \end{Bmatrix} \tag{6}$$

Eliminating the unknown inertial direction cosines from (6) by transposing (5) and substituting into (6) gives

$$\begin{Bmatrix} \ell_{s_1}(t_0) \\ \ell_{s_2}(t_0) \\ \ell_{s_3}(t_0) \end{Bmatrix} = [SG]\ [GN(t_0)]\ [GN(t)]^T\ [SG]^T \begin{Bmatrix} \ell_{s_1}(t) \\ \ell_{s_2}(t) \\ \ell_{s_3}(t) \end{Bmatrix} \tag{7}$$

From (2), $[GN(t_0)]\ [GS(t)]^T$ can be identified as $[\Phi(t, t_0)]^T$ so that (7) becomes

$$\begin{Bmatrix} \ell_{s_1}(t_0) \\ \ell_{s_2}(t_0) \\ \ell_{s_3}(t_0) \end{Bmatrix} = [SG]\ [\Phi(t, t_0)]^T\ [SG]^T \begin{Bmatrix} \ell_{s_1}(t) \\ \ell_{s_2}(t) \\ \ell_{s_3}(t) \end{Bmatrix} \tag{8}$$

with $[\Phi(t, t_0)]$ determined by numerically integrating Equation (3). This equation provides the basis for a collapsing technique that allows all star hits to be mapped into their effective sensor-fixed positions at some common epoch time t_0.

Several observations can be made concerning star identification based on Equation (8). The integration of $[\Phi(t, t_0)]$ involves only the angular velocity history that occurs between t_0 and t. Furthermore, since the differential equation for $[\Phi(t, t_0)]$ is kinematic, there are no inherent model errors in Equation (8). The only errors that are introduced are uncertainties in the rate gyro biases, B_i, and any residual instrument noise that may be present in the measured samples of angular velocity, ω_{m_i}. In the absence of these errors, all hits made by a given star as it crosses the various slits in the image plane collapse to a single point at time t_0 when processed by Equation (8). If these errors are present but reasonable, multiple hits made by individual stars still collapse to distinct clusters of points. Consequently, information is present (namely, the dispersions of the clusters) that can be used in a least squares adjustment of biases *without a priori knowledge* of the identities of the imaged stars. With unknown biases removed in this fashion, any remaining dispersions in the clusters are random under the assumption that instrument noise in the gyros is white. The best estimates of the true image plane positions of the stars, if they had been all imaged at t_0, are just the weighted centroids of each cluster. The net result of this is an instantaneous "photograph" of the star field with minimal distortions due to the motion model.

Explicit reference to vehicle orientation relative to inertial space, $[GN(t)]$, has been eliminated from (8). Clearly, an estimate of this information is required at some point in the star identification process. Since the result of the collapsing and bias adjustment process is essentially a distortion-free instantaneous photograph of the star pattern, tentative identification of a pair of stars can be made by angular separation comparisons among imaged and catalog stars. The estimate of initial orientation is now a problem only in that it must be used to determine the proper subset of the star catalog to be used for these comparisons. A large uncertainty in orientation means a large subset of the catalog must be used. However, since identification of only a single pair of stars is being undertaken at this point, the computational burden is minimized. Once two stars are tentatively identified by this technique, a deterministic orientation of the vehicle at t_0 can be computed as follows. Construct both sensor-fixed and inertial components of a right-handed set of orthonormal unit vectors according to

$$\hat{u}_1 = \hat{\ell}_1 = \ell_{1s_1}\hat{s}_1 + \ell_{1s_2}\hat{s}_2 + \ell_{1s_3}\hat{s}_3 = \ell_{1n_1}\hat{n}_1 + \ell_{1n_2}\hat{n}_2 + \ell_{1n_3}\hat{n}_3 \tag{9a}$$

$$\hat{\ell}_2 = \ell_{2s_1}\hat{s}_1 + \ell_{2s_2}\hat{s}_2 + \ell_{2s_3}\hat{s}_3 = \ell_{2n_1}\hat{n}_1 + \ell_{2n_2}\hat{n}_2 + \ell_{2n_3}\hat{n}_3 \tag{9b}$$

$$\hat{u}_2 = \hat{\ell}_1 X \hat{\ell}_2 / |\hat{\ell}_1 X \hat{\ell}_2| \tag{9c}$$

$$\hat{u}_3 = \hat{u}_1 X \hat{u}_2 \tag{9d}$$

where $\hat{\ell}_1$ and $\hat{\ell}_2$ are the unit vectors to stars 1 and 2, respectively. This system of equations can be written as

$$\{\hat{u}\} = [A]\{\hat{s}\} = [B]\{\hat{n}\} \tag{10}$$

where [A] and [B] are the $\{\hat{s}\}$ and $\{\hat{n}\}$ components of the unit vectors.

The unknown orientation of $\{\hat{s}\}$ relative to $\{\hat{n}\}$ is given by

$$\{\hat{s}\} = [SN(t_0)]\{\hat{n}\} \tag{11}$$

This expression can be combined with (10) and solved for [SN] to yield

$$[SN(t_0)] = [A]^T [B] \tag{12}$$

All candidate stars can now be mapped into the t_0 image space where the star pattern is accepted or rejected based on a direct match scheme. If the pattern is not accepted as valid, two new stars are tentatively identified by angular separation comparisons and the process is repeated from that point.

CONCLUSIONS

The development outlined herein is based on the availability of observations of the vehicle angular velocity vector. This general star identification process, however, is not restricted to that situation. If angular velocity measurements are not available, a dynamic model for the vehicle motion must be incorporated. The integration of Equation (3) then depends on the resulting dynamic angular velocity history. The dispersions within clusters of star hits after collapsing still contain information that can be used to improve parameters of the dynamic model. Implementation of the remainder of the process remains essentially unchanged.

This technique where traditional approaches are combined and modified by the generation of an instantaneous photograph is a viable approach to star identification. In cases where the collapsing is rigorous due to the availability of good angular velocity measurements and where instrument biases can be recovered because of multiple hits by single stars, this approach is a particularly attractive alternative.

REFERENCES

1. Linkens, P., *Elements of Engineering Mechanics*, McGraw-Hill, 1973, p. 105.

2. Blanton, J. N., *A New Formulation of the Free Motion of Triaxial Rigid Bodies and Applications to Satellite Photogrammetric Triangulation*, Ph.D. Dissertation, University of Virginia, 1976, pp 68-83.